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## Extinction Maps in the WFAU Archives

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### Abstract.

### 1. 3D Extinction Maps

The VSA now includes 3D extinction maps, kindly given to us by Oscar Gonzalez, based on Chen et al. (2013), which is currently available through Vizier <sup>1</sup>. However, the maps in the VSA are a slightly higher resolution ( $\Delta r = 0.5\text{kpc}$ , rather than  $1\text{kpc}$  and  $4'$  rather than  $15'$ ) and cover a slightly wider area,  $-10 < b < 5$  and  $-10 < l < 10$  than the Vizier versions, and can be used directly with the VVV survey data and other archived data sets, and can therefore use the full power of the WFAU archive interfaces.

The extinction maps consist of a 3-dimensional array of  $E(J - K_s)$  and  $E(H - K_s)$  colour-excess terms, and their errors. These are derived from fitting a model stellar population (using the Besancon model with thin disk, thick disk, bulge, and spheroid) to the VVV and Glimpse data and using the necessary adjustment in magnitude in the VVV J and Ks bands to match observations to derive an extinction measure  $E(J-K_s)$ . When J is not available (not enough sources bright enough, e.g. where the extinction is too great), the H and Ks bands were used to derive  $E(H-K_s)$ . Those derived from a wider wavelength range are more robust and should be used in preference.

Gonzalez suggests using the (Nishiyama et al. 2009) extinction law for  $|b| < 4$  and the (Cardelli et al. 1989) extinction law for  $|b| \geq 4$ . The  $\frac{A_X}{E(J-K_s)}$  and  $\frac{A_X}{E(H-K_s)}$  necessary to convert the colour-excesses to extinction values in filter X are calculated from these extinction terms. Gonzalez provides the terms for the 2MASS filter (<http://mill.astro.puc.cl/BEAM/coffinfo.php>) and we have derived the VISTA, UKIRT-WFCAM, GLIMPSE, WISE and VST terms from there.

We derive the Cardelli extinction terms for each filter using existing Cardelli values from the Spanish Virtual Observatory Filter Service<sup>2</sup> (Gutiérrez et al. 2006). The Spanish VO (and most other sources) give the correction factor as  $\frac{A_X}{E(B-V)}$ . Using Eqn. 1 we are able to convert these numbers to the required  $\frac{A_X}{E(J-K_s)}$ .

<sup>1</sup><http://vizier.u-strasbg.fr/viz-bin/VizieR-3?-source=J/A%2bA/550/A42>

<sup>2</sup><http://svo2.cab.inta-csic.es/theory/fps3/index.php?mode=browse>

$$\frac{A_X}{E(J-K_s)} = \frac{A_X}{E(B-V)} * \frac{E(B-V)}{A_Y} * \frac{A_Y}{E(J-K_s)} \quad (1)$$

where  $A_Y = A_{K_s}^{2\text{MASS}}$  for filters with  $\lambda > 1.6\mu m$  and  $A_Y = A_J^{2\text{MASS}}$  for filters with  $\lambda < 1.6\mu m$ . In each case  $\frac{E(B-V)}{A_Y} * \frac{A_Y}{E(J-K_s)} \sim 1.9$ . A similar conversion is done for  $\frac{A_X}{E(H-K_s)}$ .

We make use of Nishiyama et al. (2009) Table 1, to get the Nishiyama values for UKIRT-WFCAM and VISTA  $J$ ,  $H$  and the Spitzer-IRAC values. For the VISTA  $K_s$  and UKIRT-WFCAM  $K$  we extrapolate using the 2MASS  $H$  and  $K_s$  values and the effective wavelengths (from the Spanish VO). We also use the Spitzer-IRAC values and effective wavelengths to calculate values for the WISE W1 and W2 filters, but we have not extrapolated the Nishiyama law outside  $1.2 < \lambda < 8.0\mu m$  for which the law was measured.

## 2. WFAU Data Model

We have designed a set of new tables to store the 3D extinction maps and related data and to allow fast selection and use.

- **ThreeDimExtinctionMaps**, a table of available maps.
- **FilterExtinctionCoefficients**, a table of the coefficients to convert from colour-excess to extinction in each band.
- **vvvBulgeExtMapCoords**, a table of the pixel coordinates for VVV bulge map.
- **vvvBulge3DExtinctVals**, a table of the colour-excesses as a function of distance for VVV bulge map.

The data is stored in a different way to Vizier. Instead of having a single table, with a row for each position on the sky and every colour-excess at a different distance having a separate column, we have split the data into two tables: a table of pixels (**vvvBulgeExtMapCoords**), which contains positional information such as equatorial coordinates, Galactic coordinates, Cartesian coordinates and Hierarchical Triangular Mesh Index and each pixel is identified by a **pixelID**; a table of colour-excesses as a function of **pixelID** and distance,  $r$  (in kpc). This design is more abstract than the Vizier design and can be used for other 3D extinction maps, such as recently created ones by (APOGEE; Schultheis et al. 2014), (IPHAS; Sale et al. 2014), (Gaia-ESO; Schultheis et al. 2015) and (PanSTARRS; Green et al. 2014). We will shortly be including the IPHAS extinction map.

The final table (**FilterExtinctionCoefficients**) includes all the filter coefficient terms. The table includes filters from 2MASS, VISTA-VIRCAM, UKIRT-WFCAM, VST-OMEGACAM, Spitzer and WISE, covering most of the wide-field surveys that have observed the region covered by this 3-D extinction map. For each filter, there is an identifier, name, short-name, description and wavelength range. There are columns for  $\frac{A_X}{E(J-K_s)}$ , calculated in both the Nishiyama et al. (2009) and the Cardelli et al. (1989) extinction laws: (**aEJKsNish**) and (**aEJKsCard**), respectively, and the same for

$\frac{A_X}{E(H-K_s)}$ . Additionally, there is a column for  $\frac{A_X}{E(B-V)}$  (**aEBVCard**) taken directly from the Spanish VO, which is used in the extrapolation for the Cardelli law.

To match an object to the correct extinction map pixel, we have developed a new table-valued function `fGetPixelID(ra,dec)`, which finds the nearest pixel within  $6'$ . The results are returned as a table, not a single scalar value, which seems to be a more efficient way, possibly because SQL does the rest of the selection first and then only calculates the tabular function on the final set of rows, rather than calculating it on all positions early on.

### 3. Using Dust Maps

To match up the dust map to a small number of objects in the VVV or any other overlapping survey, a `CROSS APPLY`, or `OUTER APPLY` can be used. These apply the function to the data in the table defined before the apply term. `CROSS APPLY` is the equivalent of an `INNER JOIN` and `OUTER APPLY` is the equivalent of an `OUTER JOIN`.

```
SELECT s.sourceID, s.ksAperMag3, s.hmksPnt,c.pixelID
FROM vvvSource as s
CROSS APPLY EXTINCT.dbo.fgetPixelID(ra,dec) as c
WHERE s.sourceID=515402469078
```

```
SELECT s.sourceID, s.ksAperMag3, s.hmksPnt,c.pixelID
FROM vvvSource as s
OUTER APPLY EXTINCT.dbo.fgetPixelID(ra,dec) as c
WHERE s.sourceID=515402469078
```

where the `EXTINCT.` in front of the function is necessary because the extinction tables and function are in a different database (`EXTINCT`) from the `VVVDR2` database and SQL needs to know where to find them. Both the above cases return the same result:

```
sourceID ksAperMag3 hmksPnt pixelID
515402469078 +11.413226 +0.843723 30156
```

However, `sourceID 515793218971` lies in a region outside the table. Using `CROSS APPLY`, returns no rows, whereas using an `OUTER APPLY`, returns a `pixelID= 0`:

```
sourceID ksAperMag3 hmksPnt pixelID
515793218971 +18.182304 -9.999995E008 0
```

To get the  $J - K_s$  colour excess for the first object at a particular distance, e.g. 5kpc:

```
SELECT s.sourceID, s.ksAperMag3, s.hmksPnt,c.pixelID,e.ejks
FROM vvvSource as s CROSS APPLY
EXTINCT.dbo.fgetPixelID(ra,dec) as c,
EXTINCT..vvvBulge3DExtinctVals as e
WHERE s.sourceID=515402469078 and e.pixelID=c.pixelID
and e.r=0.5
```

returns,

```
sourceID ksAperMag3 hmksPnt pixelID ejks
515402469078 +11.413226 +0.843723 30156 +0.109000
```

Equivalent queries can also be applied to other data sets that overlap the dust maps, e.g. GLIMPSE,

```
SELECT s.seqNo, s.mag1, s.mag2,c.pixelID,e.ejks
FROM GLIMPSE..glimpse_hrc_inter as s
CROSS APPLY EXTINCT.dbo.fgetPixelID(ra,dec) as c,
EXTINCT..vvvBulge3DExtinctVals as e
WHERE s.seqNo=406 and e.pixelID=c.pixelID
and e.r=0.5
```

and given that this object matches the previous VVV object, the returned pixel and colour-excess are identical:

```
seqNo mag1 mag2 pixelID ejks
406 +10.550000 +10.563000 30156 +0.109000
```

All of the above can be done for multiple objects in a single query and with other selections applied too, e.g. selecting all sources in VVV with  $0 < l < 3$  deg and  $-5 < b < -4$  deg and  $16 < K_s < 18$  mag and  $(H - K_s) > 2$  and finding the colour-excess at  $r = 0.5$  kpc.

```
SELECT s.sourceID, s.ksAperMag3, s.hmksPnt,c.pixelID,e.ejks
FROM vvvSource as s CROSS APPLY
EXTINCT.dbo.fgetPixelID(ra,dec) as c,
EXTINCT..vvvBulge3DExtinctVals as e
WHERE s.ksAperMag3>16. and s.ksAperMag3<18. and
s.l>0. and s.l<3 and s.b>-5 and s.b<-4 and
s.hmksPnt>2. and e.pixelID=c.pixelID
and e.r=0.5
```

which returns 20 rows, which the user can try for themselves.

User created files can also be used, by selecting the *enhanced version of this form* in Freeform SQL and following the instructions. A query may look something like the following:

```
SELECT u.*,c.pixelID,e.ejks
FROM #userTable as u CROSS APPLY
EXTINCT.dbo.fgetPixelID(ra,dec) as c,
EXTINCT..vvvBulge3DExtinctVals as e
WHERE e.pixelID=c.pixelID
and e.r=0.5
```

However, for most scientific purposes, we need to calculate extinctions, not just the colour-excesses. The following selection gives the extinction and extinction corrected  $K_s$  magnitude at a distance of 5kpc.

```

SELECT s.sourceID, Ext.r, s.ksAperMag3, Ext.ejks, Ext.aKsCard,
(s.ksAperMag3-Ext.aKsCard) as ksAperMag3ExtCor
FROM vvvSource as s
CROSS APPLY EXTINCT.dbo.fgetPixelID(ra,dec) as c,
(SELECT e.*, (e.ejks*fks.aEJKsCard) as aKsCard
FROM EXTINCT..vvvBulge3DExtinctVals as e,
EXTINCT..FilterExtinctionCoefficients as fks
WHERE fks.filterID=9) as Ext
WHERE s.sourceID=515402469078 and Ext.pixelID=c.pixelID
AND Ext.r=5.

```

where it is better to calculate the extinction as derived sub-table, where it can be used in multiple places. The colour-excess-to-extinction ratios from the `FilterExtinctionCoefficients` table are used.

For VVVDR2 (and future releases), we have created a new table `vvvSourceExtinction`, which will contain matches between `vvvSource` and any extinction maps. This will contain the **sourceID**, **extMapID** and **extPixelID**, which will allow matches to multiple maps and so fast queries on hundreds of millions of sources, rather than tens of thousands will be possible. The function will still be useful for external databases where there are no matches to the VVV. The previous query can be done as:

```

SELECT s.sourceID, Ext.r, s.ksAperMag3, Ext.ejks, Ext.aKsCard,
(s.ksAperMag3-Ext.aKsCard) as ksAperMag3ExtCor
FROM vvvSource as s, vvvSourceExtinction as c,
(SELECT e.*, (e.ejks*fks.aEJKsCard) as aKsCard
FROM EXTINCT..vvvBulge3DExtinctVals as e,
EXTINCT..FilterExtinctionCoefficients as fks
WHERE fks.filterID=9) as Ext
WHERE s.sourceID=515402469078 and s.sourceID=c.sourceID and
Ext.pixelID=c.extPixelID and c.extMapID=2 AND Ext.r=5.

```

### 3.1. SEDs

```

SELECT s.sourceID, Ext.r,
(s.zAperMag3-Ext.aZCard) as zAperMag3ExtCor,
(s.yAperMag3-Ext.aYCard) as yAperMag3ExtCor,
(s.jAperMag3-Ext.aJCard) as jAperMag3ExtCor,
(s.hAperMag3-Ext.aHCard) as hAperMag3ExtCor,
(s.ksAperMag3-Ext.aKsCard) as ksAperMag3ExtCor,
(g.mag1-Ext.a34Card) as mag1ExtCor,
(g.mag2-Ext.a45Card) as mag2ExtCor,
(g.mag3-Ext.a58Card) as mag3ExtCor,
(g.mag4-Ext.a80Card) as mag4ExtCor
FROM vvvSource as s
CROSS APPLY EXTINCT.dbo.fgetPixelID(ra,dec) as c,
(SELECT e.*, (e.ejks*fz.aEJKsCard) as aZCard,
(e.ejks*fy.aEJKsCard) as aYCard, (e.ejks*fj.aEJKsCard) as aJCard,
(e.ejks*fH.aEJKsCard) as aHCard, (e.ejks*fks.aEJKsCard) as aKsCard,
(e.ejks*f34.aEJKsCard) as a34Card, (e.ejks*f45.aEJKsCard) as a45Card,
(e.ejks*f58.aEJKsCard) as a58Card, (e.ejks*f80.aEJKsCard) as a80Card

```

```

FROM EXTINCT..vvvBulge3DExtinctVals as e,
EXTINCT..FilterExtinctionCoefficients as fz,
EXTINCT..FilterExtinctionCoefficients as fy,
EXTINCT..FilterExtinctionCoefficients as fj,
EXTINCT..FilterExtinctionCoefficients as fh,
EXTINCT..FilterExtinctionCoefficients as fks,
EXTINCT..FilterExtinctionCoefficients as f34,
EXTINCT..FilterExtinctionCoefficients as f45,
EXTINCT..FilterExtinctionCoefficients as f58,
EXTINCT..FilterExtinctionCoefficients as f80
WHERE fz.filterID=5 and fy.filterID=6 and fj.filterID=7 and
fh.filterID=8 and fks.filterID=9 and f34.filterID=20 and
f45.filterID=21 and f58.filterID=22 and f80.filterID=23) as Ext,
GLIMPSE..glimpse_hrc_inter as g
WHERE s.sourceID=515402469078 and g.seqNo=406 and Ext.pixelID=c.pixelID
AND Ext.r>5.

```

where the corrected magnitude in each of the VISTA-VVV and GLIMPSE (Spitzer-IRAC) bands is calculated for each distance with  $r > 5\text{kpc}$ . For full scientific usefulness the errors should also be calculated and can use the errors in the colour-excesses.

### 3.2. Colour-Magnitude Diagram

Potentially even more useful is the locus of a star on the colour-magnitude diagram. The following query can be used to select  $M_J^e$ , the extinction corrected absolute J-band magnitude, and  $(Z - Y)^e$ , the extinction corrected  $(Z - Y)$  colour.

```

SELECT Ext.rCor,
(s.zAperMag3-Ext.aZCard-(s.yAperMag3-Ext.aYCard)) as zmyExtCor,
(s.jAperMag3-Ext.aJCard-5.*log10(Ext.rCor)-10.) as absJExtCor
FROM vvvSource as s
CROSS APPLY EXTINCT.dbo.fgetPixelID(ra,dec) as c,
(SELECT e.*, (e.ejks*fz.aEJKsCard) as aZCard,
(e.ejks*fy.aEJKsCard) as aYCard,
(e.ejks*fj.aEJKsCard) as aJCard,
(e.r+0.005) as rCor
FROM EXTINCT..vvvBulge3DExtinctVals as e,
EXTINCT..FilterExtinctionCoefficients as fz,
EXTINCT..FilterExtinctionCoefficients as fy,
EXTINCT..FilterExtinctionCoefficients as fj
WHERE fz.filterID=5 and fy.filterID=6 and
fj.filterID=7) as Ext,
GLIMPSE..glimpse_hrc_inter as g
WHERE s.sourceID=515402469078 and g.seqNo=406 and
Ext.pixelID=c.pixelID

```

where we offset the distance  $r$  by 5pc to give  $rCor$ . This offset makes no difference to the extinction values, since it is much smaller than the map resolution, but does allow us to get a value at  $r \sim 0$ , without a mathematical error.

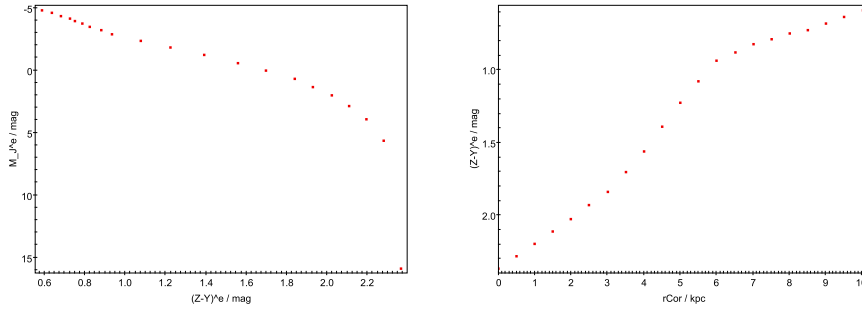


Figure 1. Left (a): Locus in the  $(Z - Y)^e$  vs  $M_J^e$  Colour-Magnitude Diagram of the VVV star with sourceID=515402469078. Right (b):  $(Z - Y)^e$  colour as a function of distance (kpc).

The locus of the star in the  $(Z - Y)^e$  vs  $M_J^e$  CMD is shown in Fig 1, as well as the variation in colour as a function of distance.

These queries can be very efficient and selections returning thousands of objects can be returned within a few minutes. The `vvvSource` table has  $5 \times 10^8$  rows. The following is a selection using a set of  $\sim 12000$  objects already selected from `vvvSource` into a FITS file that has been uploaded in the *enhanced query form*. The results are shown in Fig. 2, including error-bars. A subsample of the data with similar **sourceID** values are highlighted in blue.

```
SELECT s.sourceID, corR, (jAperMag3-5.*log10(corR)-10.-aJ) as
absJ, (zAperMag3-aZ-(yAperMag3-aY)) as zmyPntCor,
sqrt(jAperMag3Err*jAperMag3Err+aJErr*aJErr+(2.17*0.25/corR)* (2.17*0.25/corR))
as absJErr, sqrt(zAperMag3Err*zAperMag3Err+aZErr*aZErr+
yAperMag3Err*yAperMag3Err+aYErr*aYErr) as zmyPntCorErr
FROM #usertable as u, vvvSourceExtinction as c,
vvvSource as s, (select pixelID,(r+0.005) as corR,ejks,ejksErr,
(ejks*fz.aEJKsCard) as aZ, (ejksErr*fz.aEJKsCard) as aZErr,
(ejks*fy.aEJKsCard) as aY, (ejksErr*fy.aEJKsCard) as aYErr,
(ejks*fj.aEJKsCard) as aJ, (ejksErr*fj.aEJKsCard) as aJErr,
(ejks*fh.aEJKsCard) as aH, (ejksErr*fh.aEJKsCard) as aHErr,
(ejks*fks.aEJKsCard) as aKs, (ejksErr*fks.aEJKsCard) as aKsErr
from EXTINCT..vvvBulge3DExtinctVals as e,
EXTINCT..FilterExtinctionCoefficients as fz,
EXTINCT..FilterExtinctionCoefficients as fy,
EXTINCT..FilterExtinctionCoefficients as fj,
EXTINCT..FilterExtinctionCoefficients as fh,
EXTINCT..FilterExtinctionCoefficients as fks where
fz.filterID=5 and fy.filterID=6 and fj.filterID = 7 and
fh.filterID=8 and fks.filterID=9) as Ext
WHERE c.extPixelid=Ext.pixelid and c.sourceID=s.sourceID
and c.extMapID=2 and u.sourceID=s.sourceID and yAperMag3>0.
and jAperMag3>0. and Ext.corR>0.25
```

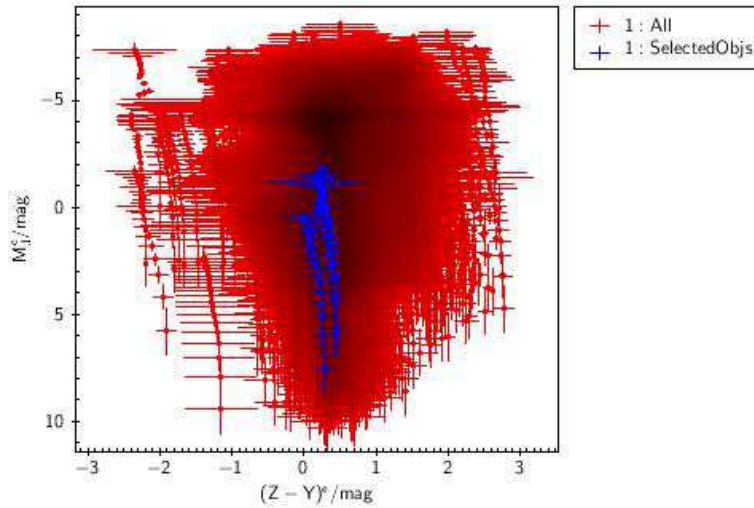
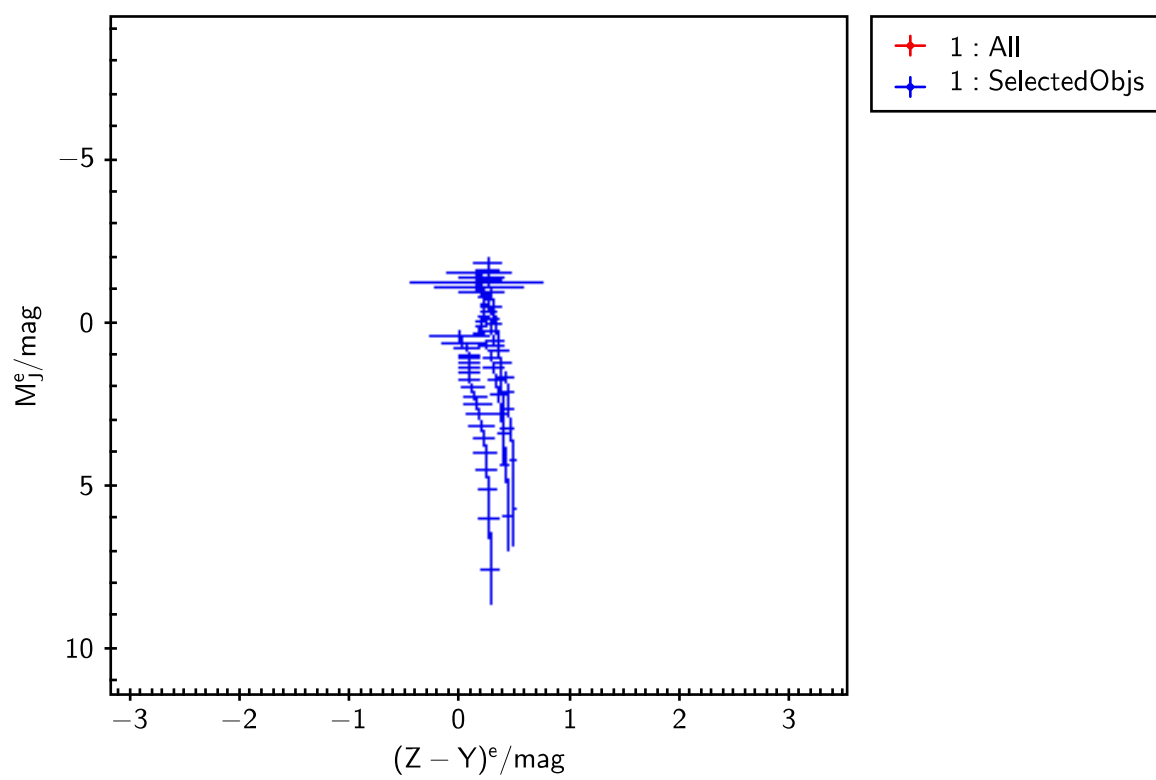


Figure 2. Locus in the  $(Z - Y)^e$  vs  $M_J^e$  Colour-Magnitude Diagram of  $\sim 10000$  VVV stars with errors included.

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This figure "CMD\_J\_ZY\_user.jpg" is available in "jpg" format from:

<http://arxiv.org/ps/1505.05157v1>